LASER SOUNDING OF THE ATMOSPHERE

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16. Abstract

Laser sounding of the atmosphere is discussed as a good prospective method for forecasting weather and for determining levels of atmospheric pollution. An explanation of the method is provided, with examples drawn from experience in determining the locations and concentrations of water vapor, sodium vapor and nitrogen. A plea is made that the technique and equipment be more vigorously developed.

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LASER SOUNDING OF THE ATMOSPHERE

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Exact information concerning the condition and composition of the atmosphere - concerning its density, temperature, pressure, humidity, concentrations of various aerosols, etc. - is important for many aspects of science and technology, but the greatest and most constant need for this information is that of meteorologists, who are concerned with solving problems of weather forecasting. In order reliably to predict meteorological phenomena, one must have excellent knowledge of the condition of the atmosphere at any given moment in time on the scale of the entire planet, i.e., obtained data concerning all important parameters of the atmosphere with an adequate degree of time and spacial density.

Existing methods of terrestrial measurements and aerological sounding of the atmosphere at various altitudes suffer from a number of unavoidable shortcomings. The radio probe cannot ascend higher that 30 m, and its ascent to the maximal altitude takes from one and one-half to two hours, and is at the mercy of winds. Aircraft and rocket sounding of the atmosphere is extremely costly, and can be performed only in certain limited regions, while the results obtained by the aid of these methods are, to a significant extent, distorted by the

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[1] Corresponding Member of the Academy of Sciences of the USSR.
* Numbers in the margin indicate pagination in the foreign text.

influence of atmospheric turbulence caused by the motions of the aircraft and rockets themselves.

Hence, there is an urgent task to develop entirely new methods for sounding the atmosphere which would ensure obtaining reliable data concerning atmospheric parameters with unprecedented spacial and time density. It is entirely clear that these methods must be remote methods, i.e., methods which permit one to conduct measurements at various distances from the instrument. Laser sounding of the atmosphere must occupy an important position among these methods.

The unusually short duration of the sounding pulse of laser irradiation automatically ensures fantastically high spacial resolution of the information thus obtained. For example, with a pulse length of 10 nsec, one can obtain information concerning a region of the atmosphere which occupies, in all, only a few meters, since the pulse of such length at a rate of propagation of 300,000 km/sec covers a portion of space which totals 3 m.

The high power of the laser pulse enables it to penetrate great distances into the atmosphere. With a receiving mirror area of ~ 1 square meter, one pulse having a power of hundreds of megawatts at a pulse length of 10-30 nsec is capable of providing reflections from the aerosol layers of a cloud free atmosphere by means of a continuous signal in the vertical direction to an altitude of 30-50 km. From this continuous signal, in principle, one can obtain information concerning continuous change in the condition of the meteoelement in time. If one uses not one, but rather a series of irradiation pulses, the sounding ceiling can be extended to an altitude of 100 km and even higher.

Modern lasers enable one to obtain tens (and more) powerful pulses per second. This means that by their aid one can investigate the dynamics of rapidly occurring atmospheric processes, for example those such as the aurora borealis.

During laser sounding of the atmosphere, particular significance attaches to a method of processing the obtained information, which arrives continuously and in high volume. For example, information concerning changes in the meteo- /87
elements or in their discreet values in a given, assigned small localization determining the volume assigned in advance can be obtained instantaneously if

the laser locator device which is employed is linked with a real time computer, and, doubtlessly, if mathematical algorithms of the single solution of the corresponding problem have been worked out in advance.

Particularly alluring perspectives are revealed in laser sounding of the atmosphere from near space, in which information is obtained on a planetary scale.

Finally, a few words about the cost of laser sounding of the atmosphere. In the development of any new method this question is far from the least important one. At first glance it can be shown that the method of sounding the atmosphere by the aid of lasers cannot compete economically with the widely used method of launching radio probes. This however is only at first glance. Actually, today the unique laser locator costs several times more than the apparatus for standard radio sounding. But, in the first place, this apparatus, in differentiation from the laser one, has been mass produced for a long time; in the second place, each launch of a radio probe requires expenditures which exceed by many times the cost of a single use of laser sounding. There can be no doubt, that in cost the method of laser sounding of the atmosphere is fully able to compete with the method of radio sounding, and even moreso with methods of aircraft and rocket sounding.

The Basic Idea of the Method and its Application in Lidars

The idea of the method of laser sounding of the atmosphere is included in the following. A pulse of laser irradiation, being propagated in the atmosphere, leaves behind itself a trace of interaction with the medium in the form of absorbed, scattered, and reirradiated photons. The interaction of the pulse of optical irradiation with the atmosphere can be manifested throughout an entire series of known phenomena: scatter in aerosols (the particles of clouds, fogs, smoke, dust, etc.); scatter among molecules of air; absorption by atmospheric gases; combination and resonance scatter by atmospheric gases; signal fluctuations caused by atmospheric turbulence.

Registering and interpreting the traces of interaction of laser pulses with atmospheric layers, one can extract information concerning pressure, density, temperature, humidity, the wind, concentrations of various gaseous components of

the atmosphere, stratification of aerosol layers, concentrations and spectra of the sizes of aerosol particles (of all types of clouds, including silver clouds, fogs, smokes, dust, hazes, etc.).

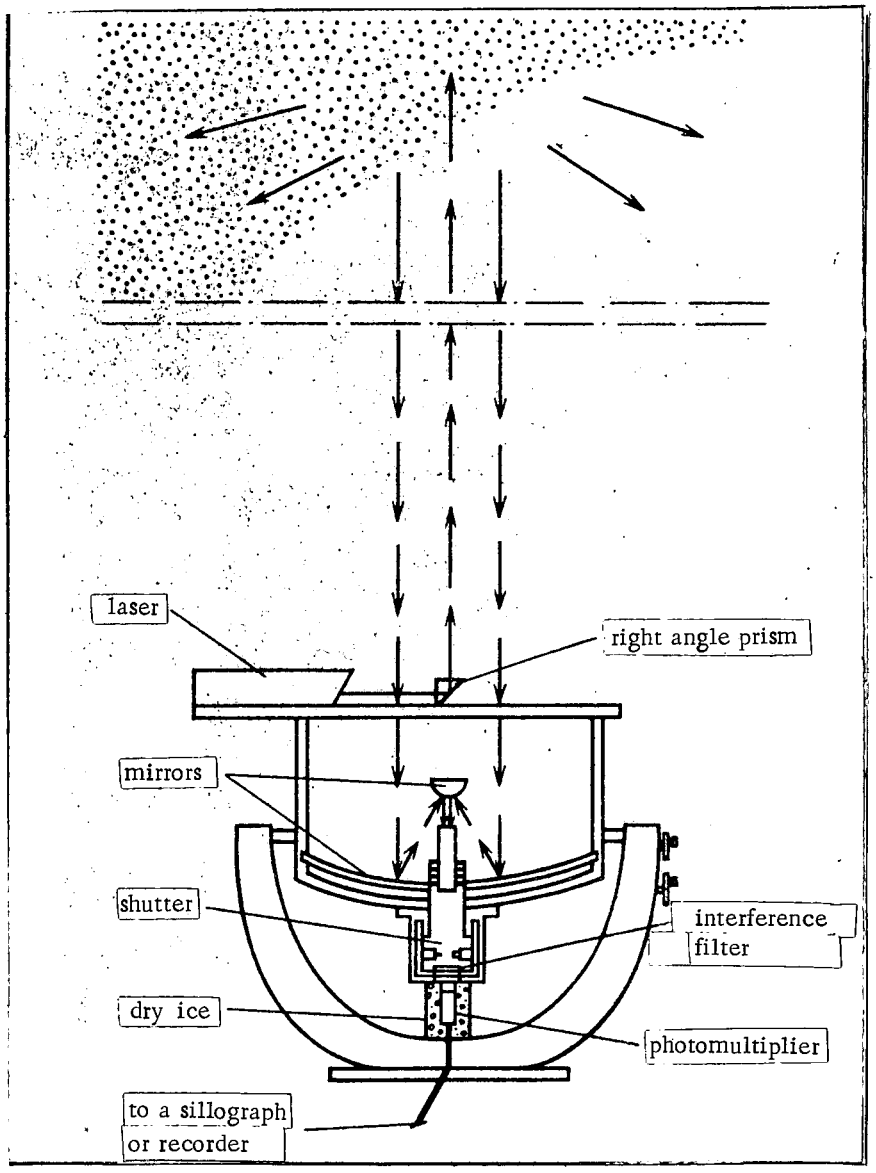

Figure 1. Diagram of a Laser Locator - Lidar - with Joint Location of both Source and Receiver.

Information concerning atmospheric aerosols can be obtained on the basis /88 of measuring energy scatter of the laser pulse by particles. Recording the energy scattered by air molecules enables one to obtain data concerning density, pressure, and temperature of corresponding atmospheric layers. The characteris-

tics of wind are obtained, for example, when measuring the change in frequency of irradiation caused by the known Doppler effect. A concentration of water vapor and other atmospheric gases can be determined by using either the phenomenon of combination scatter or the phenomenon of resonance scatter.

In combination scatter molecules of atmospheric gases, absorbing photons of the laser pulse at a certain frequency, reirradiate photons at new frequencies. The intensity of this scatter is several orders less than molecular, but it occurs at another frequency and therefore can be reliably recorded.

Resonance scatter is related to the absorption of a frequency of irradiation of the laser pulse by atoms or molecules of any atmospheric gas with subsequent reirradiation at the same frequency. In other words, the laser pulse with a corresponding resonance frequency of irradiation, passing through the atmosphere, leaves behind itself a luminescent tail of atoms or molecules. Recording the intensity of luminescence of this tail can provide us with information concerning the concentration of a gas at various altitudes. It is in fact by this means that sodium vapor was registered in the upper atmosphere. Resonance scatter has a significantly higher intensity than all other types of scatter, and therefore by its aid, in principle, one can count on obtaining information concerning extremely small concentrations of a number of atmospheric gases. But for this purpose it is necessary to have lasers with earlier known frequency of irradiation resonant for a certain gas. Such lasers already have been created.

Laser locators used for sounding the atmosphere are customarily called lidars (by analogy with radars, one of whose variations are meteorological radio locators). The operating principle of the lidar and its design are not difficult to understand if one looks at Figure 1, which depicts the system of one of the concrete designs of lidars.

By the aid of a right angle prism, the irradiation pulse of the laser is directed into the atmosphere. Encountering particles of aerosols and air molecules in its path, the irradiation of the pulse is scattered in all directions, including backward, toward the lidar. Scattering in the direction of the locator, the energy strikes its receiving antenna - a system comprised of two mirrors. The role of the large mirror consists in collecting as much of the energy

scattered by the atmospheric layers as possible. The small mirror is mounted at the focus of the large mirror. It directs the energy collected by the large mirror to the receiver - a photomultiplier.

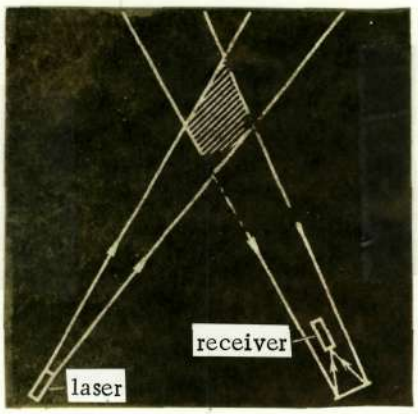

Figure 2. Diagram of a Lidar with Separate Source and Receiver. This device enables one to sound the atmosphere at various angles.

On the path from the small mirror to the receiver, the irradiation passes through a shutter and an interference filter. The shutter prevents the exposure of the photomultiplier to the powerful echo-signal of the laser pulse from layers of the atmosphere near the lidar, the layers most thickly filled with particles of aerosols and molecules of air; the shutter also prevents exposure of the photomultiplier who after glow of the laser itself (it is known that following the discharge of a light pulse, the working part of the laser can glow for a short period of time).

The interference filter plays an extremely important role in the lidar, inasmuch as the width of its bandpass and its transparency in this attitude are responsible for the relationship of the useful signal to the signal of noises of atmospheric origin (we have in mind noises of luminescence of the daytime or nighttime sky coming from various sources). The magnitude of this relationship also determines the ceiling of laser sounding of the atmosphere.

The signal from the photomultiplier is either transformed to the screen of the oscillograph and photographed, or it is recorded on magnetic tape. In this, or in any other case, for processing the recorded echo-signals a computer is usually used.

For ensuring high stability, maximal sensitivity and a decrease in dark current (intrinsic noises) of the photoelectronic-multipliers, they are cooled by means of dry ice. This is particularly important when one must work with very weak echo-signals. For example, when sounding the upper layers of the atmosphere (altitudes 30-100 km), individual photons strike the receiving device.

For obtaining a reliable result in this case, one uses information accumulator circuits while dispatching an adequately large number of laser pulses into the atmosphere.

In addition to the described lidar system, in which the optical axes of the source and receiver of irradiation coincide, one can use systems with separate transmitting and receiving devices (Figure 2).

Figures 3 and 4 show models of the apparatus of moveable lidars used in the Federal Republic of Germany for sounding the atmosphere.

Sounding the Aerosols of the Troposphere and the Stratosphere

We shall now examine the results of sounding the Tropospheric and Stratospheric aerosols, results which were obtained during work with single pulses of irradiation. The ceiling of such sounding is approximately 30-50 km for adequately powerful locators.

Figure 5 shows the relationship of echo-signals measured by aerosol and /89
molecular scatter to calculated echo-signals for molecular scatter as dependent upon the altitude of sounding. As one can see from the drawing, in all of the investigations a wide aerosol layer is found with a maximum of nearly 20 km. This layer was earlier detected by H. Young during direct measurements of the concentration of particles of atmospheric aerosol and also during optical measurements made from Soviet spacecraft[1].

Given a certain reasonable spectrum of a particle size, their index of refraction, and considering that the particles have a spherical shape, from the graph constructed one can extract information concerning the altitude path of the particles' concentration and the size of the coefficient of aerosol scatter. If one does not extract a priori information concerning the aerosol particles, during single pulse, single frequency sounding one cannot extract any quantitative data other than data concerning altitude, length, structure and relative intensity of the aerosol layers.

Today, new methods of laser sounding of aerosols are being developed which must provide the possibility of determining the spectra of sizes and concentra-

[1] See G. B. Rozenberg. The Eyes of Space. "Priroda", No. 3, 1966.

tions of particles directly from the results of sounding. In these methods, the idea of multifrequency sounding is used, as well as the idea of measuring depolarization of irradiation of the laser pulse by particles of the aerosols.

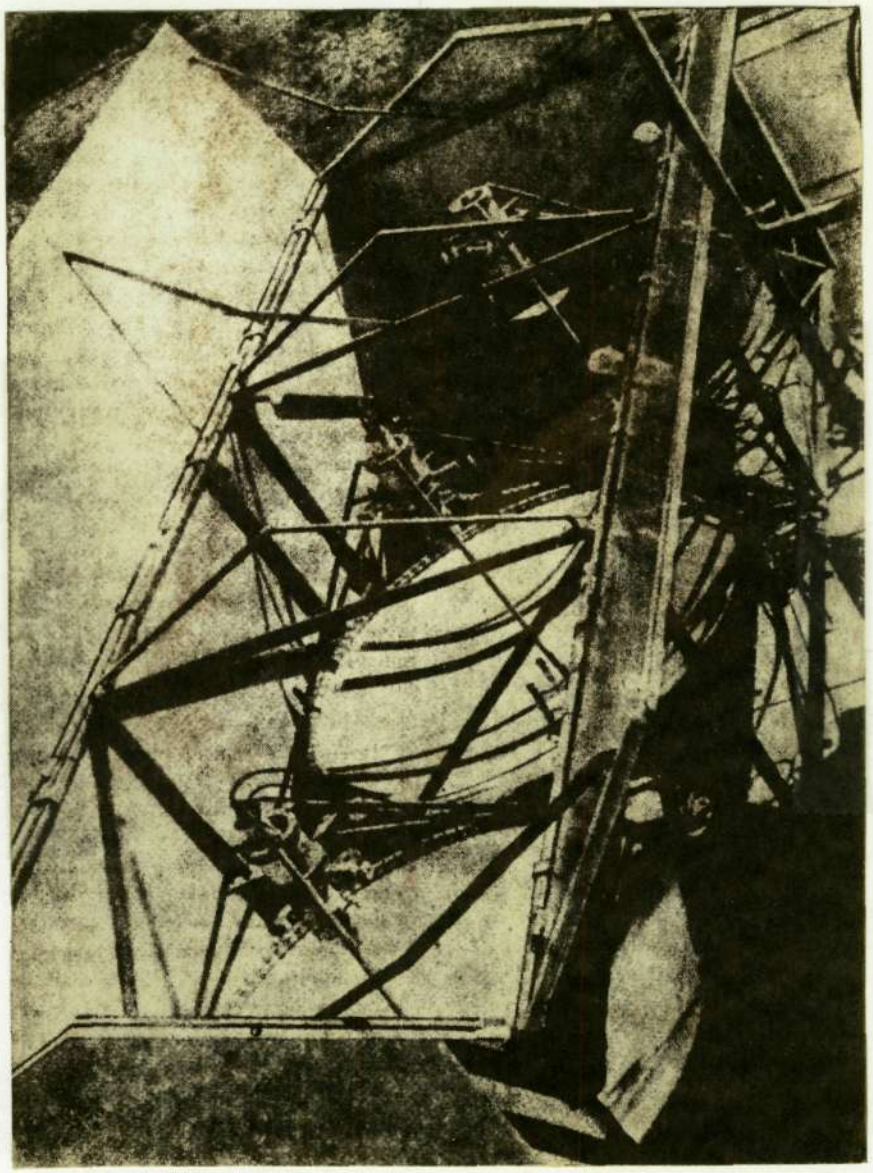

Figure 3. Overall View of Receiver Mirrors Having a Diameter of 1.5 m, at Whose Focus the Receiver of Radiant Pulses is Mounted.

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Determining the Transparency of the Atmosphere

The transparency of the atmosphere serves as an extremely important characteristic, and therefore the development of new methods for determining it are of great practical interest.

A method of determining the transparency of the atmosphere in the vertical or in an inclined direction, based upon the use of the lidar, consists in the following. If one measures the intensity of signal scatter from the same altitude, sounding the atmosphere at various angles, one can, according to the inclination of a line constructed according to the results of measurements within certain coordinates, determine the transparency of a layer of the atmosphere between the locator and the volume of atmosphere under investigation at a given altitude. And since during sounding by the single pulse method one obtains a constant curve of values of the intensity of backscatter from various altitudes, by the aid of this method one determines the transparency for a given layer, and consequently, change in transparency with altitude.

Graphs constructed according to the results of measurements within certain coordinates must yield straight-lines, if the atmosphere is homogeneous in the horizontal direction. If this condition is not satisfied, straight-line relationships are not obtained and this means that the method cannot be employed for determining the transparency of the atmosphere. It follows here, however, /90 that it can be used for controlling the horizontal homogeneity of the atmosphere.

Sounding Clouds

One can very likely state with conviction that laser sounding of clouds will be widely introduced into practice most rapidly of all. This is primarily made possible by the great value of the echo-signal which is reflected and by the possibility of obtaining data concerning clouds by the aid of comparatively simple laser locators. Also of great importance in this regard is the fact that the particles of which clouds are composed have a true spherical shape and their refraction index is well-known.

Figure 6 illustrates the application of lasers for determining the lower boundary and spacial extent of low density clouds. As one can see from the drawing, the cloud layers at altitudes 7-10 km are reliably "illuminated" by the laser locator, although in certain places their extent along the path of the impulse comprised 2 km.

In addition to boundaries of extent of clouds, it is important to know the concentration of particles, their distribution and size, the water content of

the cloud, the volumetric coefficients of scatter and reflection, and the space time picture of changes in these characteristics. Solving these type problems is not so simple, but nevertheless it has already been done in certain places. Primarily, calculations of the volumetric coefficients of scatter and the corresponding volumetric coefficients of backscatter for various types of clouds have been shown on two wavelengths: 0.69 mkm (the ruby laser) and 1.06 mkm (the glass neodymium laser). It turned out that the relationships of volumetric coefficients of backscatter to volumetric coefficients of scatter for all of the most widespread cloud types examined differ from each other within the limits of 30%; with the exclusion of only one type of cloud, differences do not exceed the limits of from 10-15%. If further calculations and experiments confirm these figures, it means that one can directly extract information concerning the volumetric coefficient of scatter from the reflected echo-signal.

Yet another possibility for determining the volumetric coefficients of cloud scatter is related to a change in the shape of the pulse reflected from the cloud. As it was established by investigations conducted by our collective, there are clearly pronounced monotonal dependencies between the coefficient of cloud scatter and all of the characteristics of the deformed reflected pulse (width, front curve, maximal amplitude and delay time). These relationships enable us to hope for success in determining the volumetric coefficients of cloud scatter according to deformation of the laser pulses reflected from them. An additional confirmation of this possibility are the results of corresponding calculations carried out by the author and his co-workers for the pulses of ruby lasers.

Matters become significantly more complex in determining the microstructural /91 characteristics of a cloud. Obviously, one of the most effective means of solving this problem will be multifrequency sounding. As yet, this method is still in the earliest stage of development.

Sounding a Polluted Atmosphere

The problem of combatting atmospheric pollution becomes a more and more acute one with each passing year in an ever growing number of participants and facilities are drawn to it. It is entirely clear that combatting atmospheric

pollution, no matter what the origin of pollution, cannot be successful or optimal if there are no methods for making a reliable quantitative evaluation of the pollutants themselves. As yet these methods are poorly developed and not one of them permits one to carry out an operational evaluation of atmospheric pollution with adequately wide spacial and time scales.

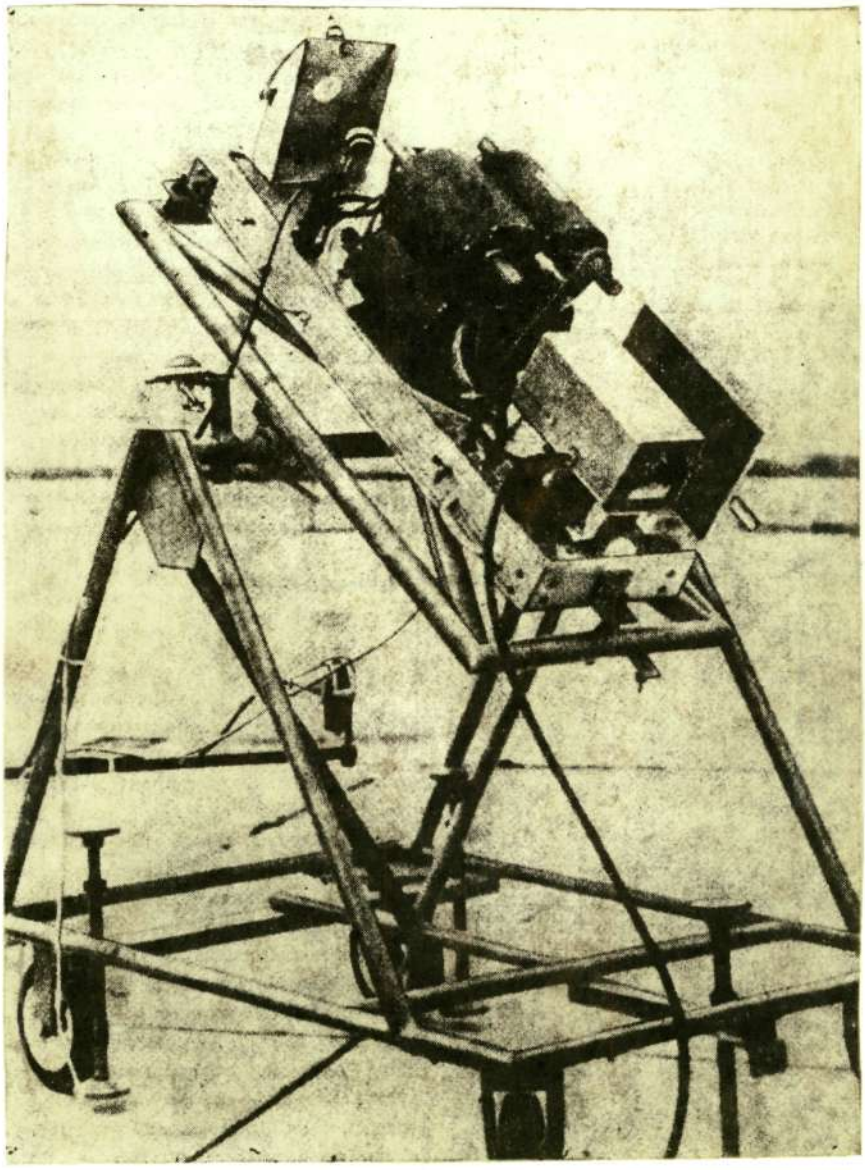

Figure 4. One Type of Portable Laser Employed for Sounding the Atmosphere.

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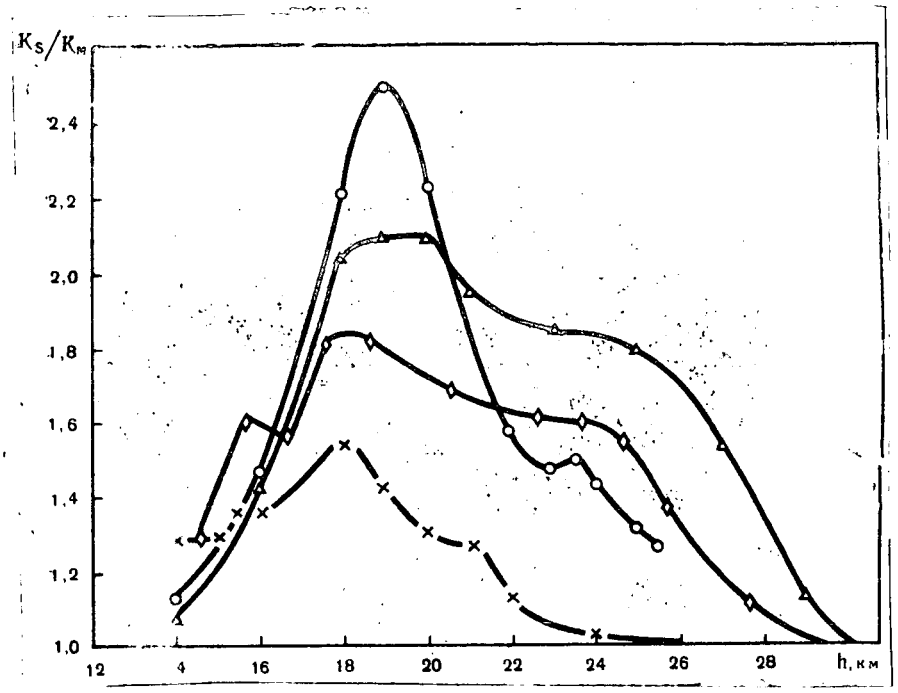

Figure 5. The Result of Laser Sounding of the Stratospheric Aerosols. Along the axis of the ordinate, the relationship of measurements of echo-signals of the aerosol and molecular scatter K_s to the calculated echo-signals of molecular scatter K_m is shown; along the axis of the abscissa is depicted the height of sounding h. The graph enables one to determine the altitude path of the concentration of the particles and the volummetric coefficient of aerosol scatter. The various curves are investigations by various authors which were conducted in different places and at various times.

A method of quantitatively estimating atmospheric pollution based upon the use of lasers is an extremely perspective one. It is primarily necessary to emphasize that by its aid one can not only quantitatively evaluate pollution of the free atmosphere in any localization of a particular region assessable to the laser pulse, but one can also in detail investigate the space-time structure of pollution. Additionally, one can study the sources of pollution and their contribution to atmospheric pollution at various distances from the source.

The perspective nature of the method of laser sounding atmospheric pollution is based upon its extremely high sensitivity. In fact, the locator catches the echo-signal from invisible particles of aerosols in relatively small concentrations. As data demonstrates pollution creates strong echo-signals which are detected by locators with quite modest energetic characteristics of the lasers.

Figure 7 shows a space-time picture of pollution of the near-Earth layer of the atmosphere which was obtained by the aid of a laser.

Determining the Parameters of the Atmosphere and Concentrations of Gases

Determining the density, temperature, and pressure is extremely important, inasmuch as the atmospheric parameters are intimately interrelated and play a significant role in various atmospheric processes, including the processes of weather development and climate. One of the methods of laser sounding in this case is based upon measuring the reflected echo-signal caused by molecular scattering of light.

The concentration of molecules of water vapor and other gaseous components of the atmosphere can be determined in various ways: by change in the reflected echo-signal on two adjacent wavelengths, one of which is forced to the center of the line of absorption of the corresponding gas, while the second is located near, but outside the line of absorption; according to resonance scatter of laser irradiation, when its wavelength coincides with the intensive lines of absorption of an atmospheric gas with a short lifetime of the atom or molecule of this gas in the excited state and when, consequently, reirradiation of the absorbed quantum of light with the same frequency occurs extremely rapidly; according to the combination scattering of light, during which process the molecules of an atmospheric gas exchange energies with the striking light quantum and within the spectrum of reirradiated energy, in addition to the frequency of the striking quantum, one observes a significantly weaker irradiation at another frequency.

The sounding data obtained today are extremely modest. This is primarily explained by the inadequate level of development of the laser technique. Presently, in all, one more or less successful attempt has been made to use the pulse ruby laser for establishing the altitude distribution of water vapor concentrations. Sounding was carried out using two pulses; the wavelength of one /92
of these was 0.69438 mkm and coincided with the central portion of the line of absorption of H_2O; the second had a total difference of 0.5-1.0 cm^{-1} (0.000035--0.00007 mkm), but still fell between the lines of absorption. If the echo--signals for these two wavelengths are known, it is not difficult to obtain a

quite simple formula for the distribution of water vapor with altitude. According to such a method, success was achieved in attaining a vertical profile of humidity for the lower 4 km layer of the atmosphere.

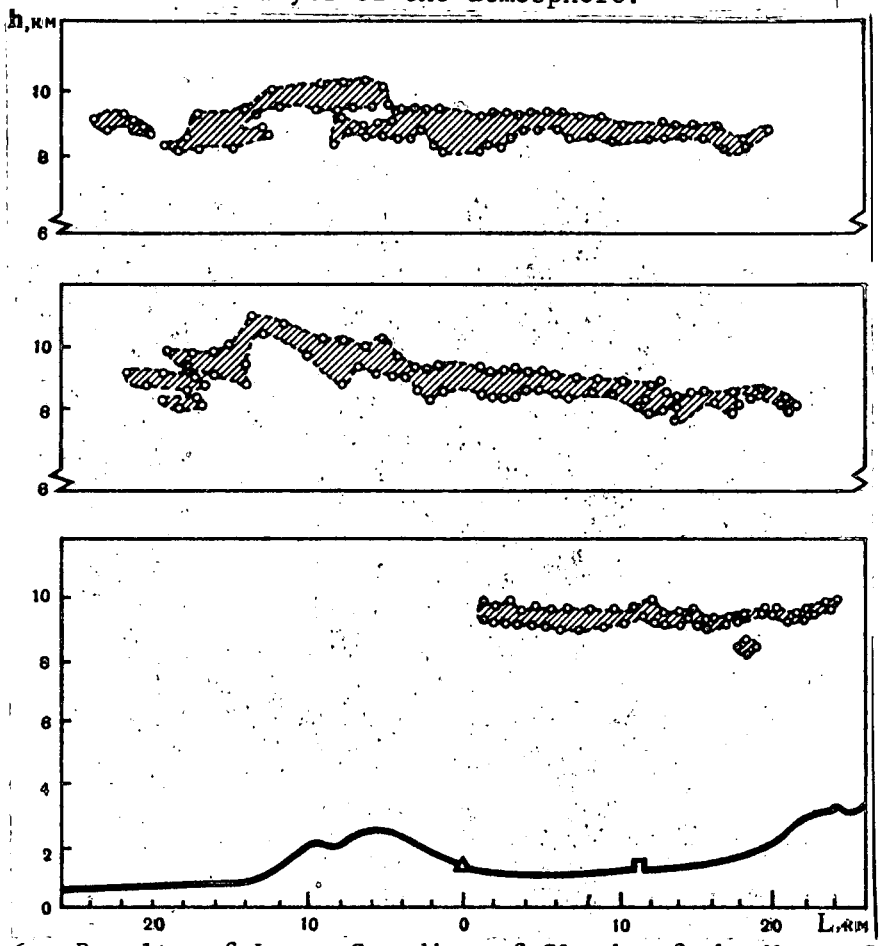

Figure 6. Results of Laser Sounding of Clouds of the Upper Stratum. The lower portion of the drawing shows a profile of the terrain where the measurements were conducted (California, USA). The triangles designate the location where the lidar was located; this lidar emitted pulses at various angles in the vertical plane, which coincided with the direction of the wind. In the upper and midportions of the drawing, results are shown of sounding weak cloud layers located at altitudes of from 7-10 km. Each pulse of irradiation is designated by 2 points which pertain to the lower and upper boundaries of the cloud layers or by 4 points in the case of two cloud layers. L is the distance from the locator.

The phenomenon of combined scattering of light was used by certain investigators for determining the profile of concentration of molecular nitrogen - a basic component of the atmosphere. The generating source, in this case, was also a ruby laser with a wavelength of irradiation of 0.6944 mkm. The wavelength

of the line of combined scattering of nitrogen molecules was 0.8285 mkm. The height of sounding did not exceed 10 km, since the intensity of this line is approximately 3 orders less than the intensity of molecular scattering on the same line.

When sounding the atmosphere by means of laser pulses for molecular nitrogen (wavelength of irradiation 0.3371 mkm), success was achieved in recording lines of combined scattering of nitrogen molecules (wavelength 0.3658 mkm) and of oxygen (wavelength 0.3557 mkm). The height of sounding was also less than 10 km.

Resonance scattering was used for determining sodium vapors in the upper atmosphere. This example is an excellent demonstration of the potentials of the method of laser sounding, when technology places in the hands of the investigator a generator with the very same parameters which he requires for his work. Sodium atoms have two intensive lines of irradiation at wavelengths 0.5890 and 0.5896 mkm (the yellow doublet of sodium is known). In the experiment, a red laser was used which had a tuneable irradiation wavelength. Hence, one could sound the atmosphere with an irradiation whose wavelength coincided with one of the lines of the sodium doublet, which not only permitted reliable detection of the presence of sodium at altitudes of from 80 to 100 km, but which also permitted measurement of its concentration and distribution with height. An investigation was also made of the time-space picture of the distribution of sodium vapors at such altitudes. And in fact their maximal concentration was billionths of the amount of concentration of nitrogen and oxygen at the same altitudes!

A Glance into the Future

Laser sounding of the atmosphere, as a principally new method of remote investigation of various atmospheric phenomena in the Troposphere, Stratosphere, Mesosphere, and Ionosphere, doubtlessly, has a vast future. The various and interesting potentials of this method will be embodied in practice as fast as two basic problems are solved which directly influence the progress of a remote study of the atmosphere by the aid of lasers: the development and creation of

new location systems and the development of mathematical algorithms for unambiguously obtaining information from the results of sounding.

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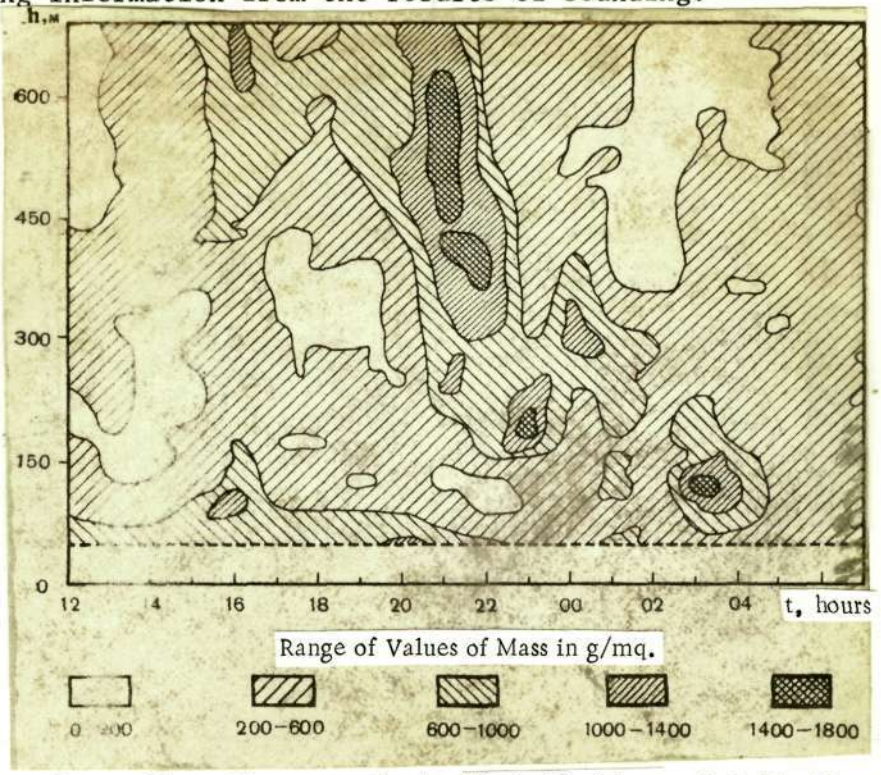

Figure 7. Space-Time Picture of the Distribution of Pollution of the Atmosphere which was Obtained by the Method of Laser Sounding at Altitudes Ranging from 0 to 650 m Over a Period of 19 Hours. The degree of pollution fluctuates from 0 to 1800 g/mq.

New laser location systems must primarily be constructed using the ideas for multifrequency sounding of the atmosphere. This idea can be realized by the aid of lasers with changeable frequency or a series of lasers with discreet frequencies. Possibly, one can also achieve the same system by using other lasers as well. This will become clear when the theoreticians who are working on the problem for unambiguous extraction of information design types of apparatus which cover the gamut of wavelengths necessary for solving various concrete problems.

The second important part of the apparatus problem is that of increasing the energy and frequency of repeat pulses. In this process, as a rule, the pulse length of irradiation must be preserved on the order of a few tenths of a nanosecond, otherwise there will be a deterioration in spacial resolution.

Finally, for solving many concrete problems of laser sounding of the atmosphere it is necessary to create special lasers in which the requirements for

gigantic amounts of power and a high degree of energy in the irradiation pulse will be combined with an extremely rigid requirements on the spectrum of irradiation: it must be both narrow and stable.

In parallel with improving the apparatus, and, perhaps, mathematical methods for unambiguously extracting information concerning the atmospheric parameters from the results of sounding must be developed at more rapid tempos.

In the next 4-5 years one can expect the appearance of the first mass produced meteorological lidars, at any rate those designated for highly accurate determination of the lower boundaries of clouds, for measuring transparency of the atmosphere and in inclined directions, and for quantitative estimation of atmospheric pollution.

In the next 5-10 years one can count on a gradual solution of such very complex problems as determining, by the sounding method, the concentrations and indices of refraction, size spectra of particles of atmospheric aerosols, as well as an investigation of the structure of atmospheric turbulence, the velocity and direction of wind. One should expect that in addition to a wide development of methods of laser sounding from the Earth, during this period practical embodiment will also be given the use of laser atmospheric probes on board long-term orbital space stations. In this same period there must appear, if one can so express it, a second generation of meteorological lidars - with operational processing of measurement information and transmission of the results of sounding in the form of profiles of the corresponding atmospheric parameters or numerical values of these parameters at certain standard levels in the atmosphere. Depended upon the complexity of the problems being solved, processing of the results of sounding can either be carried out by computer, built into the laser location system, or the laser can be supplied by a communications channel to a computer located elsewhere.

The subsequent development of methods of remote sounding of the atmosphere by the aid of lasers must lead to the creation of meteorological lidars with a practical completeness of automation of the operating cycle and with remote control: the results of sounding the atmosphere will be in a form suitable for direct use in weather forecasting and will be automatically sent to the corresponding computer centers.

Rapid progress in lasers also hastens the development of methods of laser sounding of the atmosphere, which in the near future will take up their due place in many investigations of the atmosphere, conducted not only in the laboratories of scientists, but also in the wide network of hydrometeorological stations.

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